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# The CRREL South Pole Tunneling System

Michael R. Walsh

January 1999



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**Abstract:** Facilities operations in a polar ice cap environment present many challenges. Coping with the extreme cold temperatures, associated wind chills, darkness during the long winter months, and blowing and drifting snow all hamper installation, maintenance, and repair. For over 40 years, the concept of using tunnels for utilities and personnel has been tried with mixed results. In 1991, the U.S. Army Cold Regions Research and Engineering Laboratory initiated a project to design, develop, fabricate, test, build, and deploy a system for the machining of unlined

tunnels at the Amundsen-Scott South Pole Station. The tunneling system as configured during the January 1996 deployment was capable of operating at a maximum sustained production rate ( $>4$  hr) of 1.5 m/hr for a 2-x 3-x 116-m tunnel. The maximum operating depth was approximately 16 m from surface to the tunnel floor. The maximum length tunneled during one shift was 13 m, and the maximum one-day progress was 21.3 m. The system is described in this report, along with suggestions to improve the current technology.

**Cover:** The tunneling machine at the entrance of the tunnel, Amundsen-Scott South Pole Station (U.S.A.), January 1996. (Photo by M.R. Walsh).

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# CRREL Report 99-1



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## **The CRREL South Pole Tunneling System**

Michael R. Walsh

January 1999

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National Science Foundation  
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## PREFACE

This report was prepared by Michael R. Walsh, Mechanical Engineer, Engineering Resources Division, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire. Funding for this project was provided by the National Science Foundation, Office of Polar Programs (NSF-OPP) under Technical Events T-310 C, T-380, and T-384.

This report was technically reviewed by Dr. Paul W. Richmond, Research Mechanical Engineer, CRREL, and John H. Rand, South Pole Station Modernization Project Engineer, NSF-OPP. Editing was done by Edmund Wright of CRREL.

A project of this magnitude is never the work of one person. Over 100 individuals participated in the tunneling project at CRREL. Among the most significant contributors were Donald Garfield, who was the principal investigator from the project's inception through the first deployment to the South Pole, Dennis Lambert, Larry Gould, James Morse, Christopher Williams, Troy Arnold, John Kalafut, Ronald Poulson, and William Burch. In Antarctica, we received invaluable help from Martin Lewis, Carlton Walker, Tommy Barker, and Steve Bruce of Antarctic Support Associates (ASA) and Jerry Marty of NSF at the Pole, and Roy Egeland of ASA at McMurdo Station. Without the help of all these people, this effort would not have been a success.

This report is dedicated to the memory of W. Randy McGilvary, Research Mechanical Engineer at CRREL, who developed the numerical models used in the initial analyses of the feasibility studies of the unlined tunnel concept. Randy's many talents and unbounded enthusiasm are sorely missed by all of us.

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# The CRREL South Pole Tunneling System

MICHAEL R. WALSH

## INTRODUCTION

There are few places on Earth with an environment as harsh as the U.S. Amundsen-Scott South Pole Station in Antarctica. At an elevation of over 2,830 m and with a mean temperature of almost  $-50^{\circ}\text{C}$ , field operations are difficult at best. Even in the austral summer, the mean temperature for the warmest month is only  $-28^{\circ}\text{C}$ , and with wind speeds gusting to as high as 24 m/s, wind chills can be brutal. As the station is located at the Pole, where the atmosphere thins, the physiological elevation can reach 4,250 m, resulting in shortness of breath, fatigue, and sometimes altitude sickness.

The Antarctic Plateau is a featureless, barren plain with snow accumulation of only about 8 cm (water equivalent) per year (Mosely-Thompson et al. 1995). The South Pole Station is the only significant feature on the plateau for thousands of kilometers and, as such, is plagued by the accumulation of drifting snow (Fig. 1). At one time, drifting snow threatened to overrun the 16-m-high geodesic dome that is the landmark of the U.S. station. The station has already accumulated over 8 m of snow, and it is only through the diligent efforts of the operators of two large snow dozers that the station has not been overwhelmed.

Facilities construction and maintenance at the South Pole Station are obviously a major challenge. The drifting snow makes surface placement problematic, as any item placed on the surface quickly drifts in and disappears. The low temperatures and high winds make construction and maintenance both difficult and dangerous, especially during the winter months when little or no daylight is available. Compounding these problems is the utter isolation of the station during the "winter" season, which stretches for over 250 days. If a critical facilities function fails in this time span, the station and its 28 inhabitants are in serious jeopardy.

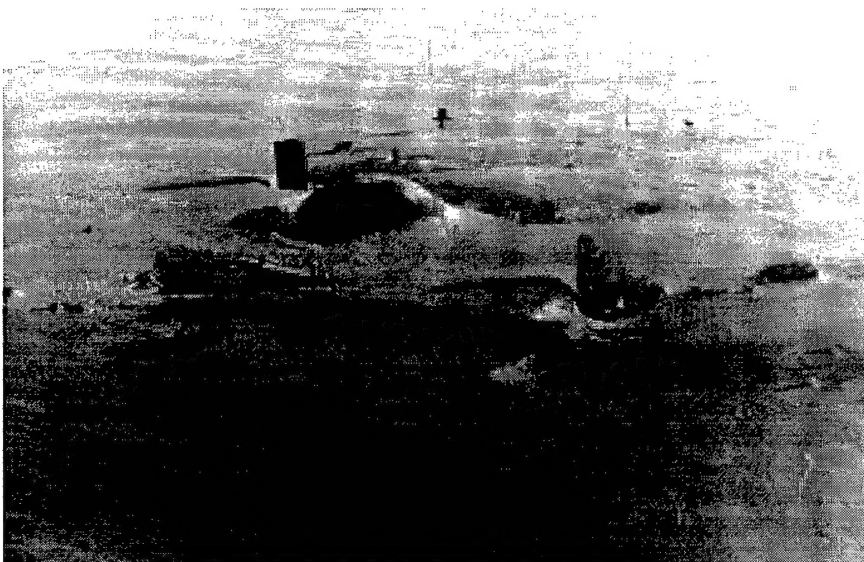
In 1991, engineers from the U.S. Army Cold

Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire, proposed to the National Science Foundation (NSF), the U.S. Government entity with responsibility for the U.S. Antarctic Program, that the construction and use of unlined tunnels at the South Pole Station may be a feasible concept for the safe and secure transport of personnel and utilities between the various structures that have grown up around the central dome. With the need for a new, expanded station being advocated by NSF, the construction and use of the tunnels will allow the old station to be connected to the new facility without the problems generated by surface structures and utilities. Seeing the merit of such a concept, NSF tasked CRREL to design, build, test, and deploy a tunneling system for use at the South Pole Station.

## BACKGROUND

Tunnels of various forms and construction are neither new nor uncommon in extreme cold regions. Their advantages are several: protection from the elements, a stable environment, elimination of drift accumulation, and ready access to utilities are just a few. The U.S. Army investigated tunneling concepts in ice and snow in the 1950s and 1960s when it was deeply involved in research in northern Greenland. Work at Camp Tuto, Camp Century, and the Distant Early Warning (DEW) ice cap radar stations all involved tunnels.

At Camp Tuto, near Thule AFB, tunnels were bored into the edge of the ice cap in 1957 using modified hard-rock mining equipment and explosives (Fig. 2). These tunnels were constructed primarily in ice. The tunnels were instrumented and snow and ice measurements taken to characterize the parameters of the material. These tunnels were unlined and, for the most part, unbraced. A small electric mining train ran through the tunnels and was used for removal of the mining debris. Work



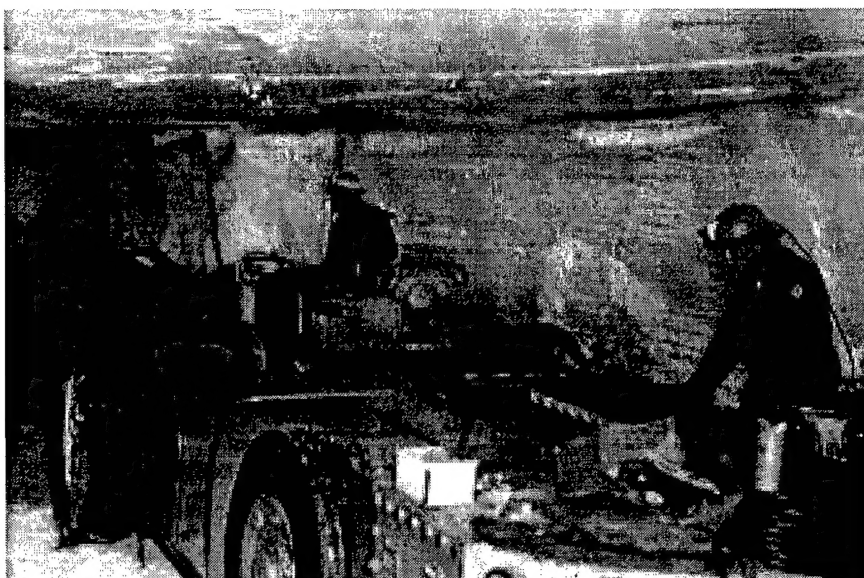
*Figure 1. The Amundsen-Scott South Pole Station (November 1997).*

was labor intensive, despite the use of heavy machinery.

Camp Century, built in 1960 by the U.S. Army and located about 150 km NE of Thule AFB, was a subsurface base constructed primarily of cut-and-cover tunnels (Clark 1965). Cut-and-cover tunnels are constructed by machining a trench, usually with a large snow miller. After the trench is formed, corrugated metal arches are placed above the trench, and the remainder of the trench is back-filled using the snow miller. The metal arch supports the tunnel roof beneath the hardened machined and blown snow.

These types of tunnels are used for near-surface applications and employ two general types

of steel arches (Fig. 3). The first type is a chordal arch, sometimes called a Granco Arch (Waterhouse 1960). These large radius arches span the top of the trench and depend on the strength of the overlying sintered snow for structural strength. In some cases, these arches were removed after the snow had hardened, resulting in a totally unlined tunnel. The other type of arch used is called a Wonder Arch (Clark 1965). These arches are approximately semicircular and form the top and sides of the "tunnel." In some cases, a trench is machined before installation of the arch to add vertical clearance to the structure. Wonder Arches are designed to be more permanent structures and, due to their size, are not easily removed once buried. In most



*Figure 2. Tunneling in Greenland (1957).*

*Figure 3. Cut-and-cover tunnel construction in Greenland (1959).*



cases, the arches are either buried under machine-blown snow or allowed to drift in. Controlled burial is preferred, as this method results in a more even loading of the arch.

Wonder Arches were still in use in Greenland through the 1980s. The Greenland DEW line sites, built in 1959–60 and abandoned around 1990, were primarily above-surface structures with column footings based on more stable subsurface snow. Fuel for operating these sites was stored beneath large Wonder Arches, originally surface structures but buried under the accumulated and drifting snow at these sites ( $\approx 1$  m/yr). Access to the fuel storage area and waste pit was via subsurface lined tunnels.

When stations were constructed in Antarctica after the International Geophysical Year (1956), construction techniques developed in Greenland were employed for subsurface structures. Unfortunately, problems associated with partially lined tunnels in Greenland were also carried over to Antarctica. These problems include settlement and subsequent deformation and crushing of the structures (Fig. 4), partial closure of unlined surfaces due to deformation of the walls and floors, maintenance difficulties, and the problem of what to do with the supporting structure after closure of the facility (Clark 1965).

As an alternative to the lined tunnel concept, a means of creating unlined tunnels was investi-

*Figure 4. Distortion of maintenance tunnel at Byrd Station, Antarctica (1967)*

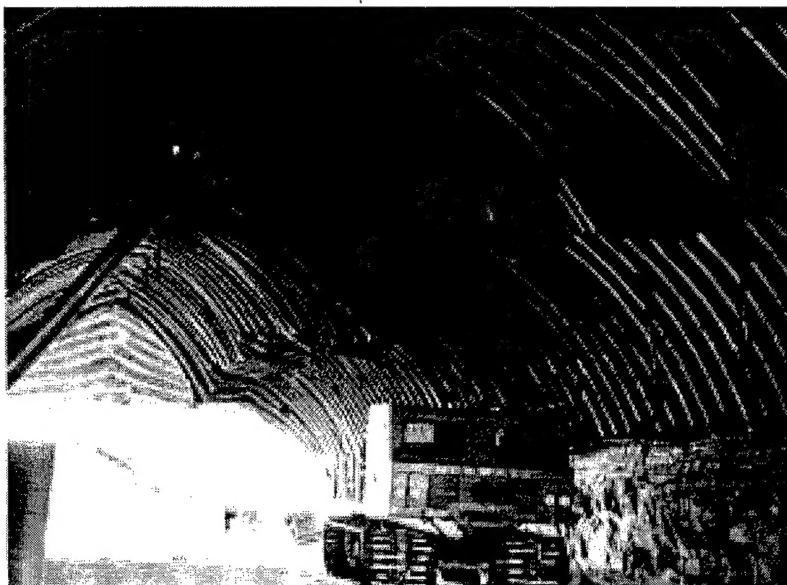




Figure 5. *The Russell Miner (Greenland, 1965).*

gated. In 1963, CRREL developed the Russell Miner, a machine specifically designed for tunneling in snow and ice (Fig. 5). Although somewhat effective at machining snow, the two-phase pneumatic transport system used by the miner, which consisted of a series of vane-axial fans, was prone to freeze up and breakdown. Tests in Greenland at Camp Century in June of 1965 demonstrated the crippling flaw of the system, the tendency of the fans to ice up and clog. Much development work was needed to enable the system to operate effectively, and the program was dropped. However, very valuable lessons were learned over the course of the Russell Miner's development, lessons that were directly applicable to the South Pole tunneling concept.

## THE UNLINED TUNNEL

As previously noted, the concept of an unlined tunnel is not new. The unlined tunnels of Camp Tuto, Greenland, machined into ice at the face of the ice cap with heavy mining equipment, were completed over 30 years prior to the inception of this project (Abel 1961). The advantages of the unlined tunnel include construction using native materials (ice and firn), the ability to tunnel at depths greater than those to which cut-and-cover tunnels are restricted, simplicity and flexibility of design, and ease of maintenance. As with any tunnel, the ability to run utilities in a protected environment, where maintenance and repair can be

conducted without the hazards of wind, drifting snow, and extreme cold, make the concept highly desirable.

Before NSF accepted the unlined tunnel concept, CRREL ran a series of finite element model (FEM) analyses to determine the theoretical strength and deformation of the tunnel for various snow conditions (Sodhi et al. 1993). These simulations were run at two tunnel roof depths, 4.6 and 6.1 m. The model took into account both the snow load and the static load imposed by a very heavily loaded C-130 aircraft (94 t). Snow properties were taken from Mellor (1975) and Gow and Ramseier (1964). Both cases indicate the tunnel will not fail, but a 6-m minimum overburden was recommended because of the uncertainties inherent in all mathematical models.

In November of 1991, CRREL engineers ran two different series of tests at the South Pole to help verify the model through the collection of empirical data (Fig. 6). The first series of tests entailed the construction of a "half-scale" model of the tunnel, 1 × 2 m in cross section, 13 m long, and 3.3 m below the surface of the snow. A bulldozer with a ground pressure in the 43- to 47-kPa range was trafficked over the tunnel a distance of 7.6 m from the entrance. No failure occurred under this condition, which simulates a 2- × 3-m tunnel 6.3-m deep under a 98-t load. The tunnel roof was raised to 2.3 m below the surface, and another was test run, resulting in a crack forming in the tunnel ceiling. This corresponds to a tunnel depth of 4.2 m. The crack, although not predicted by the model,





Figure 6. Scale model tunnel tests at South Pole.

occurred at the location the model predicted failure would occur. Failure was attributed to lower snow strength near the surface and higher loading conditions.

A final series of tests used a 1/10-scale model of the tunnel. These tests, although limited in value because of their proximity to the surface (0.6 m), confirmed the data gathered in the previous, half-scale tests. Catastrophic failure was initiated at twice the anticipated loading of the full-scale tunnel.

## THE SOUTH POLE TUNNELING SYSTEM

The CRREL South Pole Tunneling system (SPoTs) is composed primarily of five major subsystems. These are the tunneler, the chip disposal system, the surface drill rig, the generator set (genset) module, and the workshop. The tunneler and chip disposal subsystems were technically the most challenging parts of the system and thus will be discussed in greater detail. These subsystems, as well as other components of SPoTs, are under continuous development, as will be seen further into this report. The descriptions below and following are thus a snapshot of the system at the time of this report.

### System overview

Before going into detail on the system components, this report will present a brief system overview that will help orient the reader. Figure 7 shows how the system is integrated. As can be

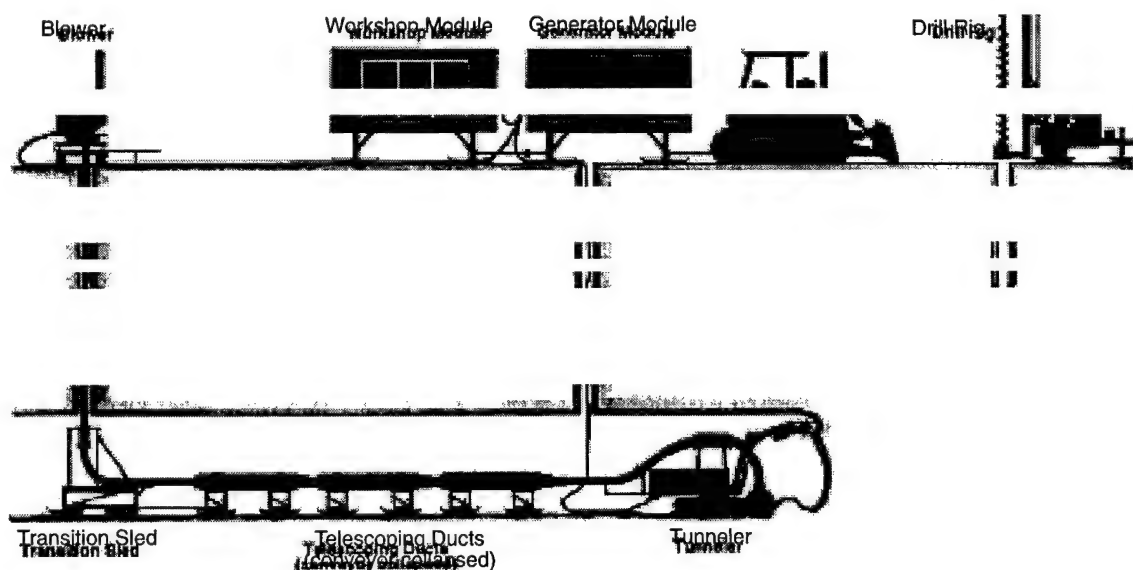


Figure 7. The South Pole Tunneling System (SPoTs).

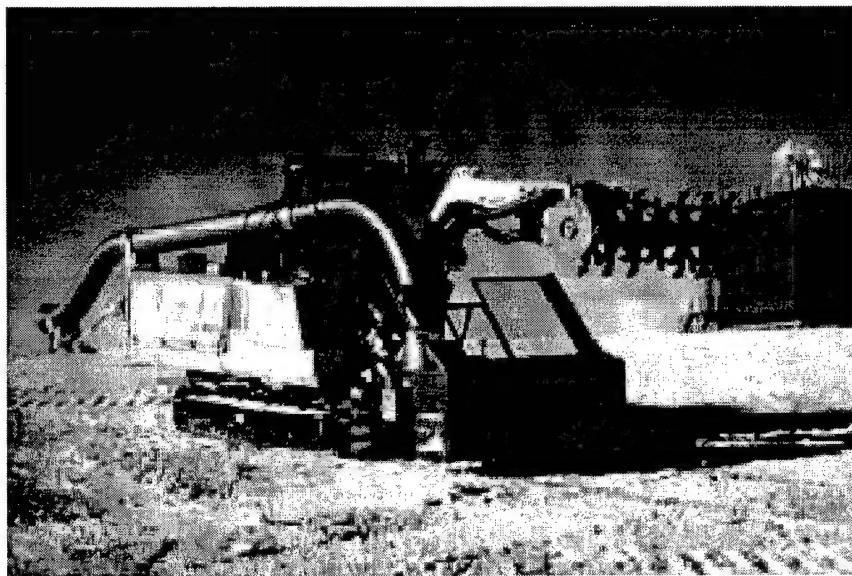
seen, the fan and drill are used on the surface, while the tunneler and chip conveyance ducting are below the surface. The tunneler machines the face of the tunnel, depositing the chips at the base of the face. A snowblower, extensively attached to the front of the tunneler, is fed into the chip pile, centering and feeding the chips into the ejector pipe going over the tunneler. Behind the tunneler, a series of telescoping duct assemblies direct the chips to the transition sled, which is also attached to a series of fixed-length vertical pipes. At the surface, the vertical pipes are attached via a flexible hose to the centrifugal fan (blower), which powers the chip conveyance system and blows the chips clear of the area. The drill rig drills the holes used for the vertical chip conveyance tubing and the power cord that supplies power from the sled-mounted generator module on the surface to the tunneler. The generator also provides power to the centrifugal fan. The workshop is used as a base of operations and to make minor repairs to the equipment.

#### **Tunneler**

When the tunneling project was initiated in January of 1992, less than a year and a half was available to develop the concept, design and fabricate the system, and test the equipment before shipment. Because of this time constraint, modifying existing equipment was chosen over the development of new designs for most of the subsystems. The basic tunneler concept is based on a

modified Melroe Bobcat 231 excavator with a Kubota BL2576 snowblower mounted to the front for chip removal (Fig. 8). The dipper stick and bucket of the excavator have been removed, and in their place a hydraulically powered rotating shaft with a series of adjustable cutter arms was designed and installed for machining the tunnel. An electrohydraulic power pack was mounted on an extended frame behind the existing diesel motor on the excavator for operating in confined spaces. The tracks on the excavator were extended 60 cm to the rear of the machine to lower the ground pressure and balance the machine. A frame was built for the attachment of the snowblower to the tunneler to allow the snowblower to be lifted and lowered, as well as extended and retracted, to aid in accessing the debris pile at the base of the tunnel face during tunneling operations. An extending chip ejector system was designed to bring the milled debris from the snowblower to an attachment point at the rear of the machine. Tilt indicators in the cab and on the boom of the tunneler provide the operator with information on the pitch and roll of the tunneler, as well as the angular position of the boom.

The tunneler employs a transverse rotational machining system for milling the face of the tunnel. This system, which is called the "cutting drum" or just "drum," is actually made up of a series of diametrically opposed cutters on axially mounted cutter arms (Fig. 9). These arms are mounted to hubs along the axis of rotation such



*Figure 8. The tunneling machine.*



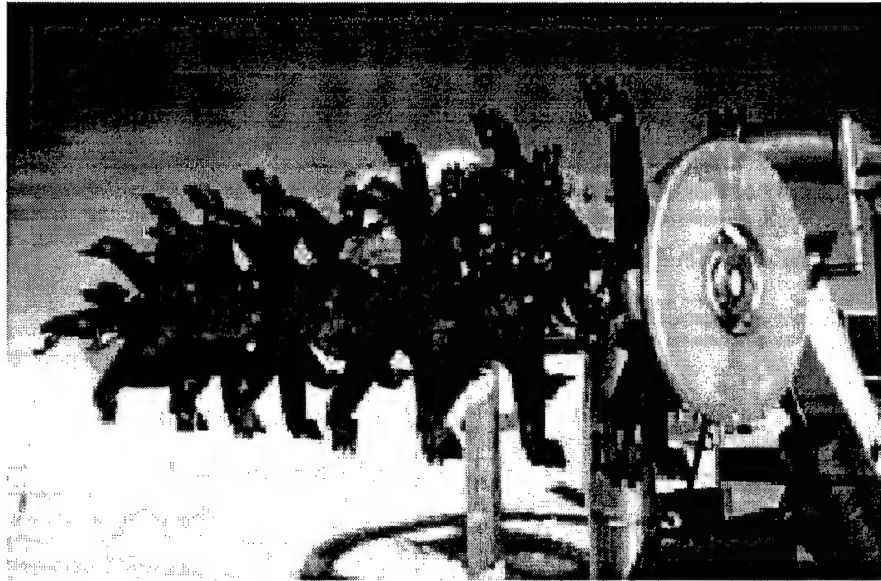


Figure 9. Close-up of the cutting drum.

that 360° rotation in 15° increments can be made to the tangential position of the cutters around the axis of the shaft. The cutters are toothed, with an 11°-clearance angle and a 24° top rake. Cutter geometry is based on work done by Ueda and Kalafut (1989). Due to the brittle nature of the material to be machined, no chip breaker was machined into the cutter. The cutters were originally to be bolted to seats on the arms, but distortion during welding of the seats to the arms resulted in mounting difficulties, so the cutters are tack welded to the seats. This modification has worked well, as the cutters are easily removed by grinding off the weld.

A total of 26 cutter arms are used to span the 1.84-m-long drum. The drum is 0.6 m in diameter with a maximum in-feed depth of 15 cm. In-feed is limited by the flange diameter of the hubs used for mounting the arms. The number of arms can be adjusted using spacers and various width cutters (Fig. 9). Three cutter widths are currently used: 5, 6.4, and 7.6 cm, with the 6.4-cm cutters the most common. The cutters are toothed, with 1.27-cm-wide teeth opposing nontoothed sections on the opposite end of the same arm. This results in larger disaggregation chips during machining and less work for a given amount of material removed. Cutter arms were originally mounted to the flanges in 45° tangential increments, with arms arranged nearly symmetrically around the center of the drum where the drive is located. Linear engagement along each 45° increment was 40.6 cm

for six of the eight rows, with the other two rows engaging 43.2 cm of the tunnel face. This resulted in near-even loading and a smoother cut as each series of cutters engaged the material.

The original drive for the drum was a fixed-speed axial vane hydraulic motor with a 7.07:1 gear reducer (Von Ruden 25S-207-A-12). A 1-in.- (2.54-cm.-) pitch stainless steel roller chain (no. 80) transferred power between a 21-tooth drive sprocket and a 28-tooth drum sprocket. Two Duralon® bearings support the 6.35-cm-OD × 1.6-cm-wall 4340 CD seamless hollow drum shaft. A pivoting mechanism that allows the drum to be rotated 90° for maneuvering the tunneler in the confines of the tunnel was incorporated at the end of the boom.

The power required to drive the drum was calculated based on the projected density of the snow ( $\rho$ ) at a depth of 10 m: 0.5 g/cm<sup>3</sup>, or 500 kg/m<sup>3</sup> (Gow and Ramseier 1964). From Mellor (1977), for efficient rotary snow plow operation:

$$E_s/\sigma_c \approx 0.3 \quad (1)$$

where  $E_s$  is the process specific energy for cutting, and  $\sigma_c$  is the uniaxial compressive strength of the snow.

At the projected conditions, the unconfined compressive strength of the snow should be around 0.85 MN/m<sup>2</sup> (Gow and Ramsier 1964). By back-calculating, the process specific energy for cutting will be

$$E_s = 0.3 \times 0.85$$

$$E_s = 0.26 \text{ MN/m}^2.$$

For a 0.6-m-diam. drum rotating at 120 rpm, the tangential tip velocity of the cutters ( $u_t$ ) is 3.8 m/s. This speed was chosen as a maximum to prevent overacceleration and dispersal of cutting chips during machining. The power required to accelerate the chips should be low if the system is to be optimized, as the chips do not need to go much beyond the face of the tunnel. To determine this, the power required to accelerate the chip ( $P_A$ ) needs to be compared to the power required to cut the material ( $P_R$ ):

$$P_A/P_R \approx \rho u_t^2 / (2 \times E_s) \text{ (Mellor 1977).} \quad (2)$$

Plugging in the values for the anticipated situation, we get:

$$P_A/P_R \approx 0.03.$$

This translates to a ratio of chip acceleration to material disaggregation of about 3%, a very low number. Other sources give much higher unconfin ed compressive strengths for snow at the South Pole (Mellor 1964, Ramseier 1963), so this should be a conservative number. In any case, this result is quite acceptable for the tunneling application, where we don't want a lot of power going into accelerating the chips.

To calculate the power required to disaggregate the firm at the face of the tunnel, a production rate needs to be established. For our purposes, we used 3 m/h as our forward progress rate, for a production rate  $Q$  of 18 m<sup>3</sup>/hr (in situ). According to Mellor (1977):

$$P_R = E_s \times Q. \quad (3)$$

Plugging in values for the production rate and cutting energy,

$$P_R = 1.3 \text{ kW.}$$

This is the theoretical cutting power requirement. Actual power required will be higher due to system inefficiencies ( $N_E$ ) and the acceleration of the chips

$$P_T = (P_R + P_A) / N_E. \quad (4)$$

Using combined inefficiencies of the hydraulic system of about 50%, and mechanical inefficien-

cies of the drive and bearing systems that are about the same, the actual required power could be as high as 5.2 kW (7 hp).

The original excavator hydraulics incorporated three 587-cm<sup>3</sup>/s (9.3 gpm) gear pumps operating at 17.2 MPa (max.) for powering the system. As the operational speeds of the various components on the reconfigured excavator would not need to be as high as originally designed, maximum flow to these components was halved. The three control circuits were fed by two electrically driven pumps, a 328-cm<sup>3</sup>/s gear pump and a 574-cm<sup>3</sup>/s gear pump, operating through a 50:50 splitter. A 660-cm<sup>3</sup>/s gear pump powered the drum, while a 215-cm<sup>3</sup>/s gear pump powered the snowblower. Flow rates for the drum and snowblower pumps were derived from the motors used for each device. The two control circuit pumps were tandemly mounted on one end of a double-shafted electric motor, with the other two pumps tandemly mounted to the other end. Maximum power available from the hydraulics is 30.7 kW, including 11 kW for the drum circuit. The next-largest size electric motor commercially available was a 37.3-kW model, which allows some room for upsizing the pumps. A high-efficiency 460-V motor of this size is used for this application. The motor and pumps are protected from high startup torque and inrush amperage with a Baldor/Lectron soft-starter, rated to 75 kW. A thorough description of all systems and components is included in the *South Pole Tunneling System Operation and Maintenance Manuals*, a four-volume set of manuals written for NSF to accompany the system (Walsh et al. 1997).

All operator controls are contained within the tunneler cab. These include the following:

- Tracks forward and reverse
- Creep-feed circuit for tracks: forward only (toggle switch)
- Cab swing (limited)
- Boom elevation
- Drum cutters rotate (toggle switch)
- Drum pivot (toggle switch)
- Snowblower elevation
- Snowblower extension
- Snowblower impeller actuation (toggle switch).

The functions actuated by toggle switches are on/off functions. The switches are mounted on a pendant control hanging to the right of the operator, and indicator lights on the control show which function is energized (Fig. 10). Both the boom el-

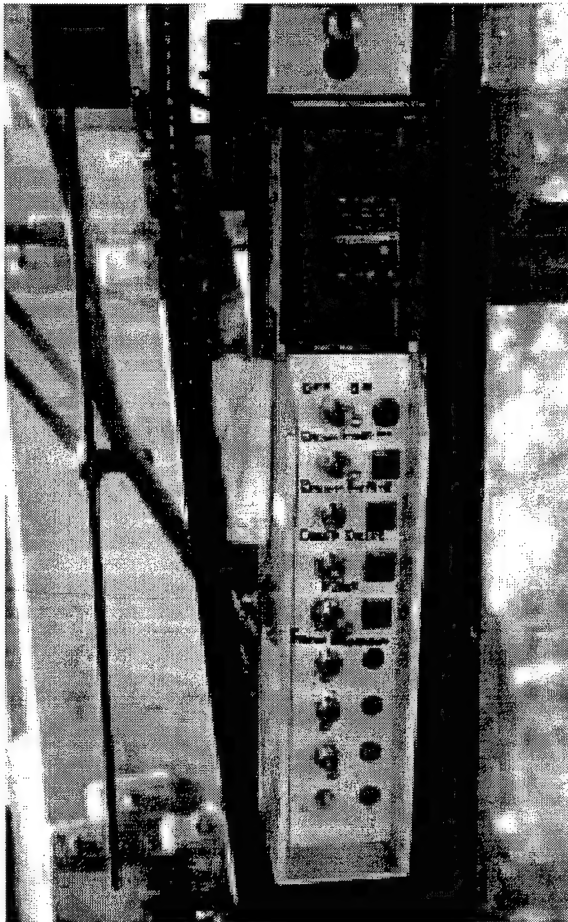


Figure 10. Control pendant in tunneler operating cab.

evation and creep feed circuits have flow control valves in line to limit the maximum component speeds. The boom elevation rates are controlled from within the cab. The creep-feed speed valve, used to limit the infeed speed of the drum into the face of the tunnel while driving the tunneler forward, is located in the rear of the tunneler near the solenoid valve controlling the circuit. The boom's slew circuit pedal on the floor has been covered with a metal guard to prevent its actuation, which will potentially damage the wiring and hydraulic hoses added during the equipment modifications and running adjacent to the boom. Cab swing is restricted using the swing lockup pin, located to the right of the operator. This allows a few degrees of rotational motion of the cab for cornering and alignment, but not enough to damage the hydraulic hoses running beneath the cab.

Inside the cab, various readouts critical to the operation of the system are available (Fig. 11). A vacuum gauge, which taps into the ejection line adjacent to the cab, allows the operator to monitor available suction on the discharge system. Available suction with no load is approximately 18 in. of water (4.5 kPa) at the cab when all chip transfer components are on line. When the reading drops below 10 in. (2.5 kPa), the system is overloading and needs time to recuperate. This gauge was critical to the smooth operation of the system and saved us many shutdowns. The reduction in the number of times the fan had to recover from

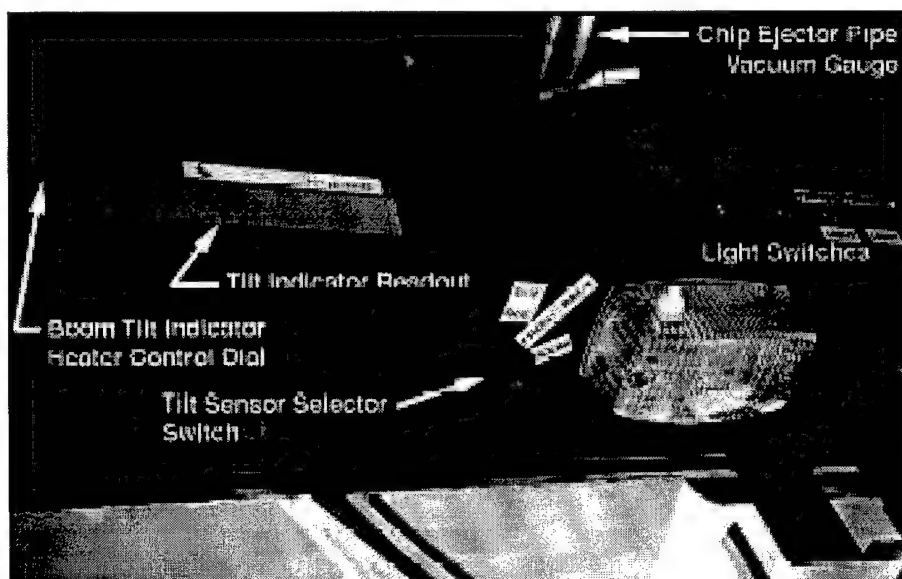


Figure 11. System function readouts in tunneler cab.

large speed reductions may even have saved the replacement blower motor. A temperature gauge for the hydraulic oil is also located in the cab. Keeping the oil temperature at an acceptable level was difficult because the tunnel was 10°C warmer than predicted. When oil temperatures exceeded 50°C, measures such as removing guarding were carried out. If the temperature exceeded 60°C, additional measures were taken to lower the temperature. If a temperature of 80°C was reached, the system was shut down and allowed to cool. A 45°C temperature drop in 20 minutes was recorded during one shutdown, so the time required for the system to cool is not long. Tilt sensors allow the operator to gauge the position of the drum as well as determine the pitch and roll of the machined tunnel. A tilt indicator on the boom provides the operator with an indication of the boom position. As currently configured, the indicator reads "0" when the tangent point at the bottom of the drum is coplanar with the bottom of the tunneler tracks on level terrain. A negative reading brings this point below level, and a positive readout raises this point. Boom angles for specific tunnel heights can be empirically determined using a measuring tape.

#### Chip disposal system

Disposal of the chips generated while machining the tunnel was the demise of the Russell Miner at Camp Century and difficult at best with the rail system deployed at Camp Tuto. The main problem with the Russell Miner system was the heating of the chips during transport and their subsequent refreezing to the vane-axial fans powering the system. Pneumatic conveyance, if made to work, is vastly preferable to the trolley system deployed at Camp Tuto or mechanical conveyance systems, such as the screw augers used to replace the Russell Miner's pneumatic system. To work reliably in the harsh environment of the South Pole, a mechanical system would have to be so robust as to make deployment by hand arduous. Maintenance, especially lubrication, would also be difficult. For these reasons, pneumatic conveyance was once again considered.

The parameters for sizing a pneumatic conveyance system are air temperature, air density, solids density, solids volume, and conveyance distance. The following parameters and derivations were used in sizing the fan used to power the transport system:

- Tunnel cross section: 2 m wide × 3 m high
- Production rate: 3 m/hr

- Volumetric removal rate: 18 m<sup>3</sup>/hr (0.005 m<sup>3</sup>/s; no bulking factor)
- Mass flow rate (snow): 2.5 kg/s
- Working air temperature: -40°C
- Working elevation: 3,500 m
- Working air density: 0.98 kg/m<sup>3</sup>.

Using these parameters, the fan manufacturer (TILCO, Hampton, N.H.) sized a system with the following parameters:

- Volumetric flow rate: 1.287 m<sup>3</sup>/s
- Static pressure: 6.76 kPa
- Power requirement: 16 kW
- Impeller size: 57.5 cm diam. × 26 cm wide (304L SS)
- Impeller speed: 3318 rpm.

Tests conducted at CRREL indicated that the impeller speed was too high, so the sheaves on the fan were changed out to decrease the speed. The volumetric flow rate of the fan is now 1.210 m<sup>3</sup>/s. Using this information, the following values were derived for the new configuration:

- Mass flow rate (air): 1.164 kg/s
- Mass flow rate (combined): 3.664 kg/s
- Volumetric flow rate (combined): 1.215 m<sup>3</sup>/s
- Snow concentration in stream (steady state): 0.4% (volumetric) 68.2% (mass)
- Mixture density: 3.01 kg/m<sup>3</sup>.

The fan is attached to a sled-mounted vibration isolation platform designed to be either towed by a Spryte or forked into place. A tapered inlet has a built-in shutoff (blast gate) to assist in startup, and the outlet has a directional chute for guiding the debris (Fig. 12). Although the manufacturer noted that the fan can be placed anywhere along the discharge, we located it on the surface due to the extreme sound power levels (116 dB). The fan originally came equipped with a 30-kW electric motor that was replaced with a 37-kW motor after the original failed. The motor is protected with a Baldor/Lectron soft-starter, rated to 75 kW.

In the tunnel, the chips are conveyed longitudinally through a series of four sets of expanding tubes on adjustable trucks (Fig. 13). Directly behind the tunneler is a two-tube unit that allows 1.5 m of travel. This allows the operator to move the tunneler back and forward without stressing the large units. The large units consist of three tubes, two sliding, and allow 6 m of travel before full extension each. Collapsed total length is 16 m;



*Figure 12. Surface-mounted blower.*



*a. Overall view*



*b. Close-up of sliding seals. Left-hand seal rolled back to expose fingers.*

*Figure 13. Duct trucks.*



fully extended it is 35.5 m. At full system extension, the tubes must be collapsed and redeployed. Tube assemblies can be added as the tunnel progresses, adding to the distance between setups. They are narrow enough to pass by each other in the tunnel. Each sliding tube joint has a set of metal fingers and a silicone annular gasket that allows sliding motion but little suction loss. A 30-cm section of flexible pipe is attached between assemblies to compensate for misalignment. The ends of the assemblies can be vertically adjusted using built-in screw jacks. Although difficult starting, the assemblies can be individually moved and positioned by two people.

To redirect the chips from horizontal to vertical, a transition sled was fabricated. This is primarily a long flexible hose supported on a lightweight, ski-mounted frame. The end of the hose that connects to the expanding tubes has limited vertical freedom but a 1-m horizontal range. A blade-type pneumatic shut-off valve known as a blast gate is incorporated into the end of the tube to cut off airflow during maintenance operations. The vertical connection end is attached to a horizontally sliding adapter, which has a range of about 15 cm. This allows alignment with the vertical tubes lowered through a drilled access hole from the surface. All connections between assemblies are made using Voss ring clamps.

A series of vertical tubes, lowered from the surface using a tripod, guides the chips from the tunnel to the surface (Fig. 14). These tubes, ranging in length from 3 m to 60 cm in length, were originally connected together using quarter-turn latches. After several tubes became disconnected and plunged down the access hole, the connections were redesigned to accept low-profile Voss clamp rings. The lowest vertical pipe segment used is 1.2 m long with a nested flexible hose for vertical adjustment and alignment to the transition sled adapter. Total vertical adjustment is 1 m. At the surface, a tube with a flange is used to anchor the vertical tube assembly. A flexible hose and sliding tube assembly connects the fan to the vertical pipes.

### Drill rig

The drill rig is a Simco 2400 SK-1 trailer-mounted drill with special CRREL-designed skis to allow easy transport on snow (Fig. 15). The controls have been slightly modified to allow speed control when operating the up-feed as well as the down-feed of the drill head traverse. Heaters have been added to the hydraulic tank but have proven

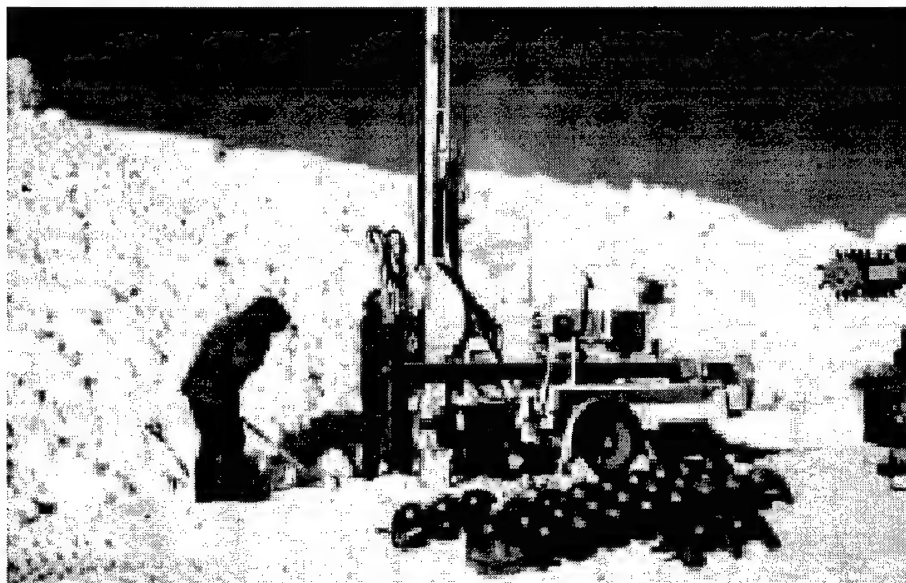
to be of limited value.

Access holes for power and chip removal are drilled using 30-cm-diam. single-flight augers. The auger is in 1-m lengths, and three assemblies have been made up using three segments each, for a total length of 9 m. One segment is left for attachment to the augerhead when starting the hole. Two augerheads are available; a short double bit head and a longer single bit head. The double bit head is generally used because of its superior cutting characteristics.

A 1-m-diam. backboring bit, designed and fabricated at CRREL, is also supplied. This bit is used for forming emergency egress shafts from the surface to the tunnel. To use the backboring bit, a 30-cm access hole must first be drilled at the location of the egress shaft. Drill string is then lowered through the hole and the bit attached. The bit is then raised while it is spinning to enlarge the hole. A 30-cm plug on the upper end of the bit keeps the bit centered in the access hole.



Figure 14. Installing vertical chip conveyance tubes.

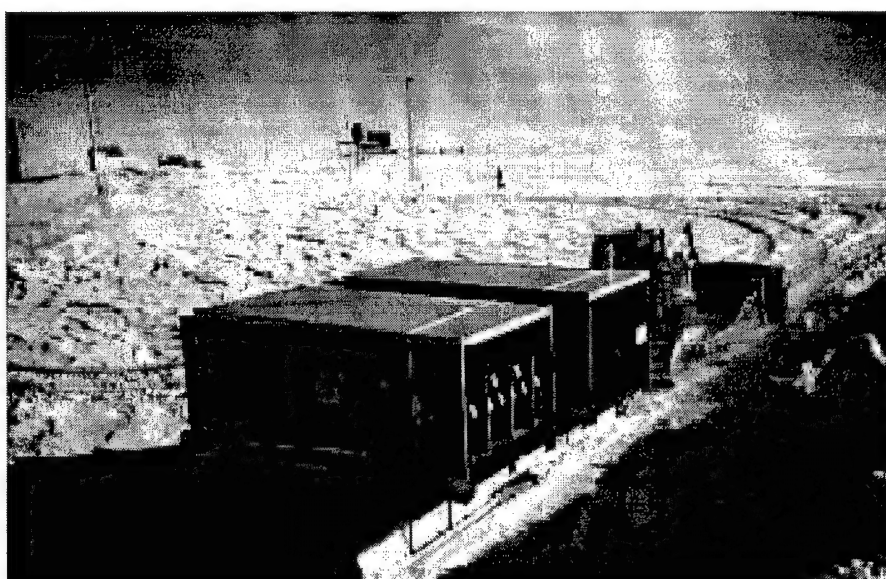


*Figure 15. Drill rig.*

#### **Generator module**

The generator module is a self-contained unit consisting of a Caterpillar 205 kVA (derated to 180-kVA), 460-VAC, 3-phase generator in an air-transportable aluminum-framed wooden module (Fig. 16). A 1,360-L fuel tank is located within the module, with the module's floor constructed to serve as a secondary containment structure in case of a fuel or oil spill. Power is fed into an eight-breaker (60-A) panel through a 300-A circuit breaker. A 1.5-

kVA, 2-phase, 120-VAC transformer off one of the breakers supplies power for lighting and accessories within the module. Power connections are made at a panel outside the module opposite the breaker panel. Power is transmitted through no. 6 Super Vu-Tron® Type-W four-conductor power cable. Hubbel® locking connectors are used at the ends. Cord sets are 23-m long each. Power is distributed through these cords to the fan, the tunnel, a warm-up shelter, and the workshop.



*Figure 16. Generator and workshop modules on 20-t sled.*

## Workshop

The workshop is enclosed in a module of similar construction to the generator module. Sections of the two side walls have Trombe walls built in to utilize passive solar heating. The workshop contains a lathe, mill/drill, small welding machine, a hydraulic hose-making setup, miscellaneous hand and power tools, spare parts and hardware (stored in metal cabinets), and the base station for the radio. Although cramped, the workshop can be a welcome relief from the cold and wind on the surface. A hazardous materials cabinet within the workshop is used for storing lubricants for the machinery associated with the project.

## TESTING

Prior to shipment of the system to Antarctica, tests were conducted at CRREL and the nearby Dartmouth Skiway in Lyme, New Hampshire. These tests were designed to check out the equipment operation, determine operating parameters, optimize systems, and check the viability of the overall concept. Although the vastly different snow conditions and temperatures lessened the value of the tests, they proved very useful in the initial refinement of the equipment design.

The tests at CRREL were the first tests of the integrated system. A small pile of snow was scraped up for feed material, and the equipment was set up from that point. A scissors lift was rented for elevating the fan to the 9-m maximum design lift height, and the expanding tubes extended to their full length to simulate maximum transport distance. Although snowing at the time of the tests, the temperatures were 45°C higher than those we would encounter at Pole. The snow was quite wet and we experienced some plugging of the tubes. Some problems with the tube extension were encountered, but these were attributed to inexperience and overfeeding at the front end by the snowblower. The fan initially performed poorly, so the drive was sheaved down and performance improved substantially. However, some lugging of the motor was still experienced. The impeller blades of the tunneler snowblower were reduced in size to cut down on the overfeeding of the conveyance system.

Tests at the Dartmouth Skiway were more rigorous, allowing a better evaluation of the system. A large mound of snow was generated by Skiway

personnel for our tests, allowing us a more realistic setup. Early morning temperatures approached -20°C, much closer to the -50°C expected at the Pole. Due to the way the snow mound was formed, however, the pile was much warmer and the snow very wet once the outer 50 cm was penetrated. Some problems surfaced almost immediately. The conveyance system was still being overwhelmed, as the chips were being fed in slugs rather than in a metered or steady state. Huge current surges occurred when the 30-kW drive motor lugged while trying to process these slugs. Adjustment of the soft-starter helped somewhat, but the cause of the problem remained. Several strategies were tested to resolve the problem, including bleeding in air at the snowblower, choking flow at the impeller, further reducing impeller vane size, choking flow at the fan, and using a dustpan arrangement instead of a snowblower for collecting chips, but none yielded satisfactory results. Because the snow was very wet (water was running out from beneath the pile) we postulated that system performance would improve at the Pole with the drier snow and lower temperatures.

The hydraulic system was simplified when many of the functions originally designed into the system were found to be unnecessary. Hydraulic oil temperatures were extremely high, sometimes exceeding 90°C. Running without the guarding helped but didn't alleviate the problem. Again, this was attributed to the higher temperatures encountered in New Hampshire. Finally, an extender was fabricated and installed between the snowblower and extension frame to better address the debris pile in front of the tunneler. Tests with the drill system, including the 1-m backboring bit, were fully successful.

The equipment was returned to CRREL and modifications made as a result of the tests conducted. The hydraulic system was extensively modified and somewhat simplified, although the usefulness of some functions still needed evaluation. Testing was conducted in a large, low-temperature facility at CRREL, which indicated that high startup torques due to high oil viscosities at low temperature may occur. Significant problems that still persisted included high hydraulic temperatures, inefficiencies in the chip conveyance system, and bogging of the fan motor. Final resolution of these problems was left for Antarctica where the system could be tested under design conditions. The equipment was prepared for shipment and left CRREL in August of 1993.



## DEPLOYMENTS

Funding difficulties delayed deployment in Antarctica until January of 1996. During this deployment, the system was assembled and tested at the South Pole Station, modified, and an attempt was made to begin tunneling operations. Equipment failures brought operations to a close shortly after starting. Following the January deployment, we returned to the Pole in November and further modified and tested the equipment. During this deployment, the proof of concept tunnel, was completed. In January of 1998, the tunneler was flown to McMurdo where further modifications were made to improve the production rate of the system.

### Initial deployment (1995-96 season)

In late 1995, four members of the design team were approved for deployment by NSF to test the machine at the South Pole Station. A proof-of-concept tunnel, originally planned for a length of 30 m at a depth of 11 m, was expanded to 125 m at a maximum depth of 16 m. It would also be a "working tunnel," used for the station's wastewater system.

Prior to the start of surface tests, the equipment needed minor repairs due to damage caused during shipment. Loss of the cutters from the arms resulted in the decision to weld the cutters to the seats, rather than bolting them in place. The integrity of the assembly was considered more im-

portant than the convenience of quickly changing out cutters. The system was assembled on the surface and tested against a mound of snow formed while trenching for the tunnel starting point (Fig. 17). Hydraulic oil heating problems again surfaced, and the guarding needed to be removed. The fan motor still lugged, albeit not as severely as at CRREL, but still enough to be of concern. Ramping up time for the motor was increased, and current limit was decreased at the soft-starter to try to reduce the strain on the motors. Some loss of control function experienced by the operator was worked around by actuating a blocked valve (deadheading) to pressurize the control circuit before activating the controls. Although this enabled the operator to actuate the controls, it exacerbated the heating problems as the deadheaded circuit vented through a pressure relief valve.

With system adjustments made, the tunneler and fan were lowered into the starting trench and tunneling commenced. Shortly after starting, the fan motor burned out. The motor was likely damaged at the Skiway in prior tests and finally gave out during continuous running at the Pole. A call was put in to McMurdo Station for a motor in the 30- to 37-kW range with the same motor frame size.

Concurrently, problems developed with the flexible stainless steel hose used to direct chips from the snowblower to the ejector tube at the rear of the tunneler. Flexing of the hose led to repeated breakage at the connection point. Attempts were



*Figure 17. Surface testing of system.*

made to reinforce this area, but failure continued.

The snowblower extension frame was modified slightly to increase ground clearance and reduce an interference problem. A cutter blade was added to the front of the snowblower to improve snow removal from the floor, and side wing extensions added to prevent machined snow from passing by the sides of the snowblower.

A 30-kW motor with the correct frame size was shipped from McMurdo to the Pole and installed on the fan. The equipment was redeployed in the trench, and tunneling recommenced. Unfortunately, within two hours, one of the electrohydraulic pump shafts failed and the equipment was down once again. On-site attempts to repair the shaft were unsuccessful, and after several attempts to rectify a seal leakage problem, the operation was terminated. While waiting for the pump shaft to be repaired, the tunneler was returned to the shop at the Pole and the flexible hose elbow reinforced with angle iron to form a fixed elbow. The ejector tube was modified to allow sliding extension when the snowblower was extended. The system, tested with these modifications under diesel power, was a vast improvement over the old system. Final progress on the tunnel was 7.5 m, about the length of the tunneler.

Although somewhat disappointing, the Antarctic trip was very valuable. Important modifications to the equipment were made, and operating experience pointed to several other areas that could be improved. Further simplification of the hydraulics needed to be made, and the source of much of the excess heat generation found and rectified: a faulty pressure relief valve for the drum circuit was not allowing oil to bypass when the drum stalled during cutting. Further analysis of the broken pump shaft at CRREL and by an independent metallurgist could not definitively determine the cause of pump failure, but fracture patterns on the shaft indicated the failure mechanism was likely high startup torque.

#### **Operational deployment (1996–97 season)**

Over the course of the summer following the initial deployment, the tunneling system had been reexamined and the hydraulics simplified to improve reliability. A new ejector chute for the front end of the tunneler was designed and manufactured to replace the flexible tube that had been so problematic in January. To reduce stress on the system of expanding tubes used for chip transfer, a short duct/truck assembly, called a pup truck, was designed for use directly behind the tunneler.

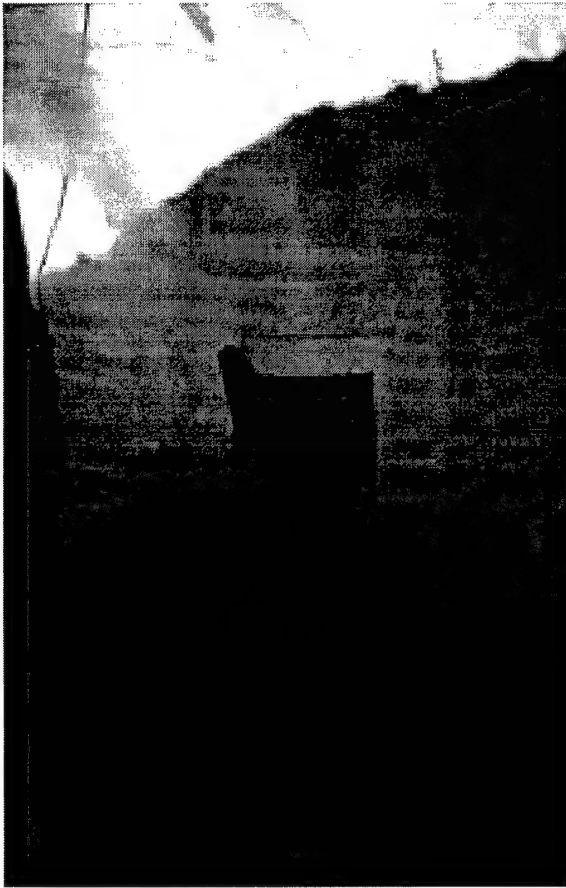
This assembly has only one sliding tube, which extends 2 m. The normal back and forth movements of the tunneler are thus translated to the lighter, more flexible pup truck.

A team of four CRREL engineers and technicians arrived at the Amundsen–Scott Station on 15 November 1996 to resume the tunneling effort. Foul weather, which led to a late opening of the summer season at the Pole, hampered the initial work planned for arrival. The equipment was deployed and modifications to the tunneler were begun with what was available from our cargo and on site.

The cutter drum was reconfigured to allow more even loading of the teeth during the cutting process. The cutter arms were rotated such that a line of cutters, symmetrical about the center chain drive where possible, engages the tunnel face every 45° rotational increment. The engaged length is either 41 or 43 cm. This is an improvement over the 10-cm spread in the engaged length on the original drum configuration and allows smoother system operation. In addition, the drum drive sprocket was replaced with a 21-tooth sprocket, increasing available torque almost 10%. The chain also needed replacement, as the installed chain had galled and no longer flexed freely.

The tunneler tracks were tightened and the cleats removed, making travel with the tunneler much smoother. The roughness of the travel on the hard firn and surface snow of the Pole had resulted in the failure of some components, most notably the shoulder bolts and piston rod extension on the snowblower lift mechanism. An adjustable choke was fabricated and installed on the impeller opening of the snowblower to limit the flow of snow into the chip-removal system in an attempt to reduce stress on the centrifugal fan motor. The broken hydraulic pump was replaced, along with the faulty drum pressure relief valve, pump heater coils were installed beneath both tandem hydraulic pumps, and some of the other modifications were implemented to simplify the hydraulics.

Testing of the system was conducted on 21 November. The cutter drum worked much more evenly than during the previous deployment, but the choke seemed to have little effect on the blower motor performance. The 30-kW motor was switched out for a 37-kW motor. The tunnel access trench was completed during the test phase, and the area at the bottom of the trench was prepared for equipment deployment. At this time, the final shipment of cargo arrived and the remain-



*Figure 18. Start of tunneling operation.*

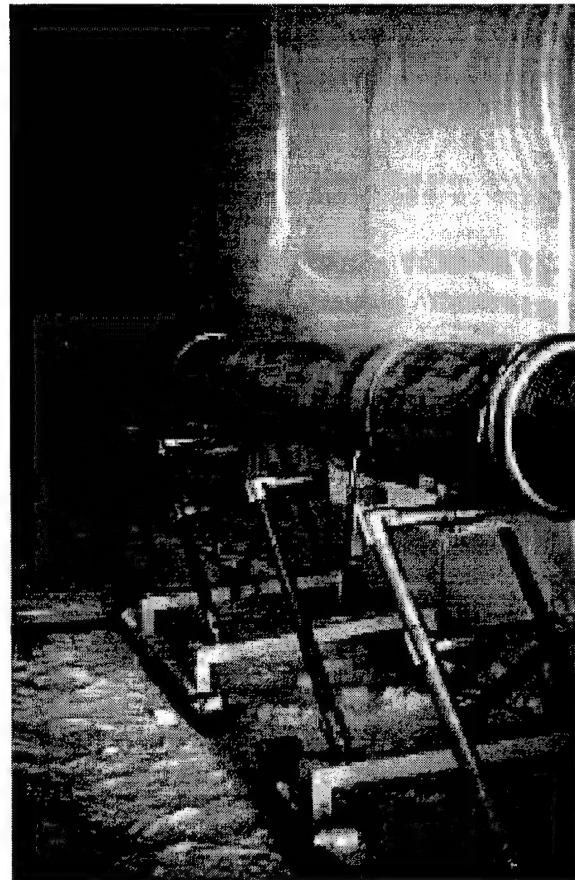
ing modifications to the system were made the following day. The system was now ready for the resumption of tunneling.

Tunneling operations recommenced on 22 November. As in January, we started with the blower in the trench with the tunneler. The initial configuration included the tunneler, the pup truck, a 3-m section of flexible pipe, and the blower (Fig. 18). As the tunneler progressed, duct assemblies were added one at a time behind the tunneler, with the pup truck assembly always directly behind the tunneler (Fig. 19). The genset and workshop modules were located on the surface, 16 m above the tunnel floor. Power cables to the tunneler and warm-up shelter were strung over the edge of the trench to the equipment.

Progress was slower than anticipated, with the first day's production rate around 1.5 m/hr, compared to the target 3 m/hr. As the tunneler got deeper into the tunnel, the production rate fell to a near-steady 1 m/hr. The critical factor was the ability of the centrifugal fan to handle the slug of

chips that periodically came through the disposal line. Frequent tripping of the circuit breaker on the fan motor controller resulted in unanticipated and bothersome delays. The tunneler controls continued to be unresponsive, resulting in inefficiencies in operations. Finally, chip removal at the base of the tunneler face was difficult because of the inadequate reach of the snowblower and a lack of torque at the drum, even though the drum torque had been increased.

Despite these problems, progress was steady. The tunneler did a very good job creating a clean, spacious tunnel. Changing the direction of the tunnel, i.e., curves and bends in the tunnel path, was easily executed. The floor level in both the transverse and longitudinal directions was easily maintained, although misinterpretation of the tilt sensor readout led us to initially tunnel down at a slight angle, rather than up as required. Because of the difficulty of maintaining pressure to the control joysticks in the tunneler, it was necessary to continually "deadhead" the controls to initiate



*Figure 19. Pup truck behind tunneler.*

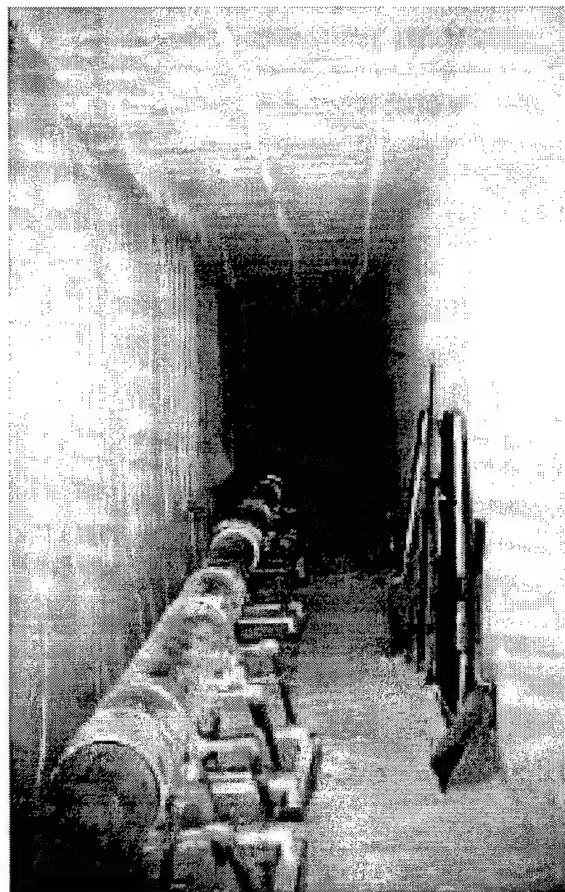
**Table 1. Horizontal chip conveyance component lengths (m).**

Component	Collapsed length	Extended length
Pup truck	2.7	4.2
Duct truck	4.4	10.4
Flexible extension	1.1	—
Transition sled	2	—

joystick operation. This led once again to high oil temperatures, sometimes reaching up to 80° C or more, despite the -40° temperature of the tunnel.

With the tunneler slowly progressing through the firm, a strategy was developed for the most efficient deployment of the duct assemblies. As Table 1 shows, the minimum length of the system in its collapsed configuration is about 5 m. This is with only the pup truck and transition sled deployed behind the tunneler. After the tunneler progresses to the maximum extension of the pup truck, the 1.1-m section of flex hose is added. When progress exceeds 4.4 m, the first section of duct assembly is substituted for the pup truck and flex hose. The pup truck is reinserted behind the tunneler as soon as possible, and the flex hose added between the duct assembly and transition sled thereafter. As progress continues, duct assemblies are added when maximum extension is reached with installed units (Fig. 20). The fully extended length when all units are installed is over 38 m, giving a total extension of over 33 m (108 ft). Using this strategy, only half as many holes from the surface to the tunnel need to be drilled for power and vertical tube access. Additional downtime is required for the integration of each assembly, but this strategy still cuts the overall downtime almost in half.

By 25 November, progress was far enough (30 m) to redeploy the blower fan to the surface, drill a set of access holes, and install the vertical tubing and transition sled. Because of the increased depth of the tunnel, 16 m vs. the original 10 m (max.), special care had to be exercised while drilling the access holes. There are two bits available for the drill, a single-cutter/single-helix bit (0.9-m long) and a double-cutter/double-helix bit (0.3-m long). Because of the hardness of the snow and the length of the hole, the double-cutter bit was required. However, the amount of drill string was insufficient to reach the tunnel roof when the double-cutter bit was used, so the drill string had to be



*Figure 20. Extended ducts in tunnel.*

removed, the bits swapped, the string relowered into the hole, and the last 0.3 m drilled. Two holes were drilled side-by-side in one location, one for the power cable, the other for the vertical ducting for the chip removal system. Survey markers on the surface were used to determine the location of the holes.

Before starting the tunneler each day, the heaters had been run for at least 45 minutes. After the first surface deployment of the blower, however, the machine was only warmed up 10 minutes, and within an hour the drum pump shaft failed. The probable cause of the failure of the pump shaft in January of 1996 could now be confirmed: inadequate warm-up time for the hydraulic system, resulting in high oil viscosity and high starting torque for the pumps. Overtorquing of the pump shafts led to overstressing of the cold, brittle shafts, initiating cracks that eventually led to torsion failure. On this deployment we were prepared for a shaft failure and had another set of pumps available. The equipment was back in operation the next morning.



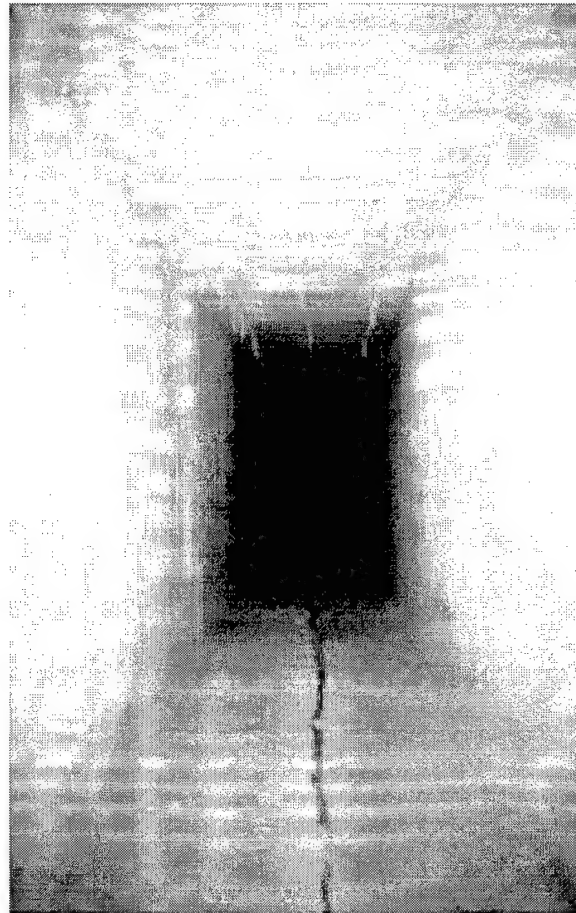
Warm-up of the drill also proved critical. The drill has a large hydraulic reservoir with under-sized heaters, and starting the drill is very difficult. If the drill is operated with cold oil, frothing occurs as the drill rotation and lift/lower hydraulic motors will cause air entrainment. Special care must be exercised with this equipment, as it is very dangerous and difficult to operate, especially when cold.

Two more sets of vertical holes were drilled over the course of the 116-m tunnel before reaching the stopping point as determined by the facilities contractor at the Pole. Because of the thinning of the overburden, the last 9 m of the tunnel was constructed using the cut-and-cover method. After replacing the pump, only minor problems were encountered with the equipment. The systemic problems, such as the blower motor tripping and the faulty tunneler controls, continued to plague operations but were worked around, albeit at a cost to productivity. Surveying errors and misinterpretation of the tilt sensor data led to a very interesting tunnel, not very straight but clean. The slope problem was partially compensated for in the last 30 m of the tunnel, the difference to be made up with cribbing of the pipe to be installed. Additional flexible expansion joints would be needed to work around the straightness problem. In the end, the tunnel was about 1.5 m off center and 30 cm lower than planned.

The tunnel was completed on 3 December, the original target date (Fig. 21). To do this, we ran two shifts the last seven days, working 12- to 20-hour days in wind chills as low as  $-80^{\circ}\text{C}$ . We often ran the equipment with only a crew of two, as manpower requirements on station did not allow assistance from the facilities contractor most days. Overall production was only a little over 1 m/hr, a painfully slow progression compared to what we expected from the equipment. However, operating the system for this extended period of time under actual conditions allowed us to examine the weak points and develop proposed solutions for the next deployment.

#### **Modifications deployment (1997-98 season)**

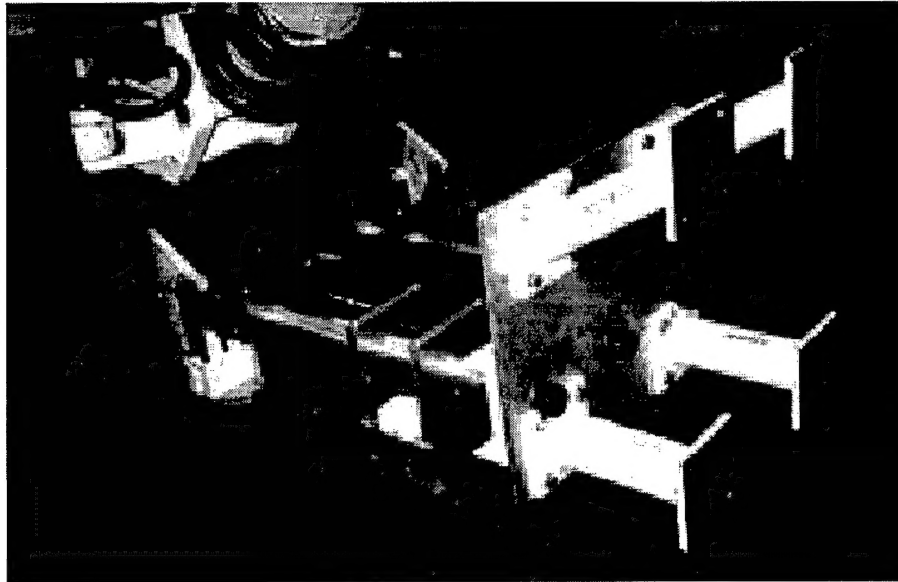
In January of 1998, two CRREL personnel returned to Antarctica to implement modifications to the equipment developed as a result of the November 1996 deployment. The tunneler, duct assemblies, and vertical tubing were shipped from the Pole to McMurdo where the work was performed. Deploying to McMurdo was chosen from a list of alternatives as the most expeditious, low-



*Figure 21. Finished tunnel (December 1997).*

est cost method of completing the work. The superior facilities, availability of specialized support personnel, on-site power, and spacious work area (compared to the Pole) were all advantages.

Conversations with the blower manufacturer after the tunneling effort had uncovered two system design flaws. The first was the way the chips were introduced into the airstream. Before modification, the air and chips were taken up through the same orifice, the impeller opening and chute of the snowblower. The manufacturer recommended that the chips be introduced into an established airstream. The elbow above the snowblower was thus modified into a wye, with the impeller throwing the chips into the airstream originating at the open leg of the wye. The second problem was at the blower end, where the chips traveled up the vertical piping, through a  $90^{\circ}$  bend, and directly into the blower. The centrifugal force acting on the mixed flow stream through the bend causes consolidation of the solids and thus com-



*Figure 22. New snowblower frame.*

promises the ability of the fan to process the material. The solution was to add a 3-m sliding tube between the elbow and the blower to allow remixure of the material in the air stream. An additional benefit is increased ease of installation, as this provides a radial degree of freedom in locating the blower in relationship to the elbow.

A new snowblower frame was installed (Fig. 22), replacing the previous unit that did not extend far enough and was not rugged enough. Two bell cranks are used to lift the frame, putting the lift cylinders in compression rather than tension and thus reducing the chance of failure. The pivots are 3.8 cm diam., a substantial increase over the previous 1.6-cm diam. pivot pins, and the assembly is lifted from two points rather than one, adding to the strength and stability of the unit.

The horizontal duct assemblies were modified to increase ease of use. The original extension stops, which did not function as planned, were removed and cable stays were added to prevent overextension of the tubes. Polyethylene was added to the tubes to decrease friction and galling during relative movement between tubes. Collapsed-length stops were also added to prevent compression of the tube seals, and the trucks were tied together with cables to reduce the stress on the system when advancing after full extension. The force of extension will now be taken up primarily by the cables rather than the components of the pup truck and duct assemblies.

The vertical ducting fasteners were replaced

with a V-groove band clamp system at this time. This system is similar to the one used on the horizontal ducting. The redesign should prevent accidental release of the tubes such as occurred several times during the tunneling operation. The lifting bale for the vertical tubing was also replaced with a simpler, easier-to-use system. Both changes will result in safer operations.

The cutter drum was disassembled and rebuilt. The cutters were realigned to allow engagement every 15°, rather than every 45°. A larger, special low-temperature chain was installed (no. 100 vs. no. 80) as the previous chain had once again galled and no longer flexed freely. The 12.7-mm hydraulic lines were replaced with 15.9-mm lines, cutting line losses in half. The drum and snowblower pumps were replaced with more robust, higher capacity pumps, thus increasing the availability of speed and torque. Cavitation due to inadequately sized suction lines prevented the completion of this task, however, although some simplification of the hydraulics was carried out.

A few smaller modifications aimed at ease of use were also made. The tilt indicators were repositioned to read "0" on the flat and level, and the inclination directions changed to be more intuitive ("+" is now up, "-" down). The accumulator valve for the tunneler was replaced, restoring functionality to the joystick controls. With these and the other modifications noted in this section, operation and production of the tunneling system should be much improved.

**Table 2. Deployment analysis—November/December 1996.**

<i>Date</i>	<i>Time on site (hr)</i>	<i>Tunneling time (hr)</i>	<i>Progress (m)</i>	<i>Production rate (m/hr)</i>	<i>Tunnel length (m)</i>	<i>Notes</i>
11/22	12	3	4.6	1.5	12.2	Start in p.m.
11/23	11.5	8	7.6	1	19.8	
11/24	9	4.5	1.5	0.3	21.3	Training day
11/25	12	10	9.1	1	30.4	
11/26	19.5	4.5	5.5	1	35.9	Drill holes/redeploy
11/27	20.5	11	9.8	1	45.7	Fix pump/blown hoses
11/28	24	16	16.8	1	62.5	Drill holes/redeploy
11/29	20	15	15.2	1	77.7	Fix blown hoses
11/30	12	7	7.6	1	85.3	Genset problems
12/1	19	3.5	3.1	1	88.4	Drill holes/redeploy
12/2	20.5	17	21.3	1.3	109.7	
12/3	12	4	6.1	1.5	115.8	Finish in a.m.

## RESULTS

The tunneling system as configured during the January 1996 deployment was capable of operating at an average production rate of just over 1 m/hr, one-third of the target production rate. The maximum sustained production rate (>4 hr) was 1.5 m/hr. The maximum operating depth was approximately 16 m from surface to floor, 6 m greater than the design depth. Maximum total linear run for snow transport was 59 m, including an 18-m lift from the tunnel floor to the eye of the centrifugal blower fan. The maximum length tunneled during one shift was 13 m, and the maximum one-day progress was 21.3 m. Approximately 54% of the shift time was devoted to productive tunneling operations. The remainder was absorbed in preparations for moving the equipment, preparing vertical holes, equipment repair, downtime due to meals, and training. Table 2 summarizes the tunneling activities of November through December 1996.

## CONCLUSIONS

The CRREL South Pole Tunneling System is a workable option for creating tunnels at the South Pole. The system as deployed in 1996 had some serious drawbacks, most of which were addressed either during the tunneling operations or during subsequent modifications made in McMurdo Station in 1998. As with any prototype, the flexibility built into the system added greatly to its complexity and thus its susceptibility to breakdown. Sys-

tem simplification since the initial deployment has resulted in increased productive time and production. A complete rebuild of the tunneler, transforming it from a prototype to a "preproduction" system, is recommended, but budgetary constraints will probably exclude this option. In either case, the South Pole Tunneling System is the first total system capable of machining tunnels in the upper region of an ice cap.

An economic analysis of the system is premature at this time, as CRREL is still working with a prototype system that needs optimization. The original analysis called for a production rate of approximately 3 m/hr to be more cost-effective than a cut-and-cover system. Therefore, on a direct dollar comparison, the tunneling system as it stands is not economically feasible. However, that analysis was based on a crew of eight personnel, whereas we found that operating with three to four is possible, albeit a good deal more strenuous. If the production rate can be doubled to 2 m/hr, tunneling should be competitive with other methods of forming tunnels. In any case, the use of tunnels for passage and utilities is clearly preferable over surface structures from the standpoint of safety and maintenance of equipment, especially in winter.

The unlined tunnel machined in 1996 is currently being utilized at the South Pole Station for the wastewater outfall line (Fig. 23). Shortly after the installation of the line, during the 1996–97 winter-over period when the Station was isolated from physical contact with the outside, the outfall line failed. At the time, wind chill on the surface was around  $-70^{\circ}\text{C}$  and daylight was limited. The repairs were quickly made to the line in the lighted tunnel (at  $-40^{\circ}$ ) without personnel having to ven-

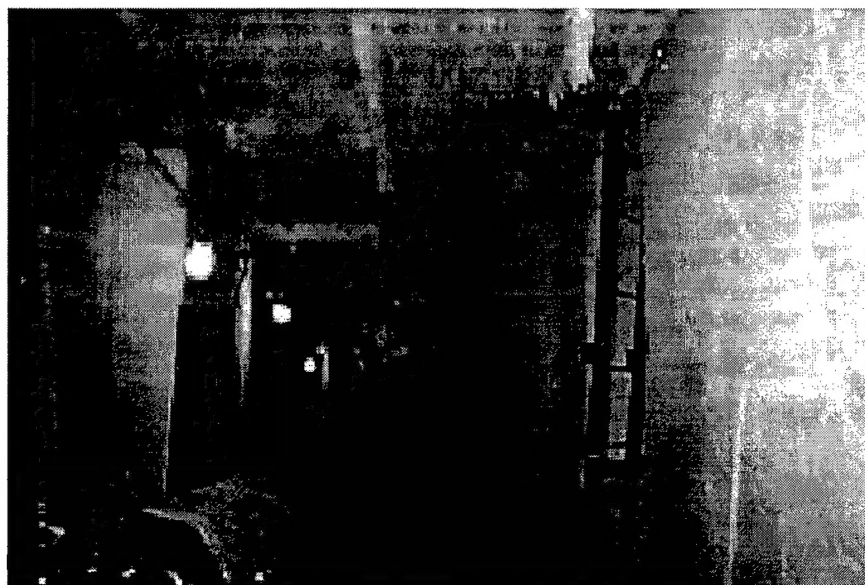


Figure 23. Wastewater line installation in tunnel.

ture outside. No damage to the line occurred. As part of the daily maintenance routine at the station, the outfall is checked twice a day. Again, this can now be accomplished in a well-lit, controlled environment without risk to personnel. The unlined tunnel and the system designed to machine it have already proven to be a useful addition to the safe and effective operation of the U.S. Amundsen-Scott South Pole Station.

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Facilities operations in a polar ice cap environment present many challenges. Coping with the extreme cold temperatures, associated wind chills, darkness during the long winter months, and blowing and drifting snow all hamper installation, maintenance, and repair. For over 40 years, the concept of using tunnels for utilities and personnel has been tried with mixed results. In 1991, the U.S. Army Cold Regions Research and Engineering Laboratory initiated a project to design, develop, fabricate, test, build, and deploy a system for the machining of unlined tunnels at the Amundsen-Scott South Pole Station. The tunneling system as configured during the January 1996 deployment was capable of operating at a maximum sustained production rate (>4 hr) of 1.5 m/hr for a 2-x 3-x 116-m tunnel. The maximum operating depth was approximately 16 m from surface to the tunnel floor. The maximum length tunneled during one shift was 13 m, and the maximum one-day progress was 21.3 m. The system is described in this report, along with suggestions to improve the current technology.

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